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Systematic Study of the Solution Properties of Low Global Warming Potential R-404A Replacement Refrigerant Blends with Various Polyol Ester Lubricants

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ABSTRACT

This paper extends our previous investigations of refrigerant/lubricant property optimization to refrigerant blends; in particular, to nonflammable low global warming potential replacements for R-404A (GWP= 3952) with GWP < 1500. Solution phase behavior and solution property data are reported for R-449A/B and R-448A in combination with three POE lubricants of varied chemical structure, and corresponding varied solubility/miscibility with the refrigerant. When comparing refrigerant blends with a single lubricant, R-449A/B and R-448A gave a lower isobaric suction condition viscosity curve than R-404A; suggesting that these new refrigerant blends may give improved compressor energy efficiency at low operating temperatures. The results suggest that, although each polyol ester lubricant exhibits very different miscibility behavior in the refrigerant blends, the resulting solution viscosities at normal operating conditions is nearly identical for the isobaric suction curves. However, there were differences observed in the solution viscosities in the isobaric discharge condition curves. The overall conclusion is that there may be opportunities to improve frictional and wear performance through optimization of lubricant properties depending on compressor design and operating conditions. All three refrigerant blends can use the ISO 32 POE lubricants currently in use with R-404A without any detriment to performance or reliability.

1. INTRODUCTION

Lubricants are important components of almost all air conditioning and refrigeration systems. Their primary function is to lubricate the compressor, provide sealing of clearances between low and high pressure sides of the compressor and remove frictional heat. But the lubricant is in contact with refrigerant at all times in the refrigeration cycle and plays a thermo-fluidic role that can impact both system capacity and coefficient of performance (COP). Lubricants can influence capacity by altering the refrigerant-side heat transfer coefficients, and increasing pressure drop required to maintain set point temperatures. Lubricants can also affect the isentropic efficiency of the compressor. Recent research has conclusively demonstrated that the optimization of lubricant/refrigerant properties can provide improvements in energy efficiency and COP (Benanti, 2014).

The transition to lower global warming potential (GWP) alternative refrigerants is critical to the realization of environmentally sustainable and more energy efficient refrigeration technologies (Ritter, 2013). Leading candidates to replace R-404A (GWP= 3922) include refrigerant blends R-448A and R-449A/B; having GWP in the range of 1250-1400 [IPCC AR4].

2. EXPERIMENTAL

2.1 Refrigerant/Lubricant Miscibility Measurements

Glass tubes were charged with predetermined volumes of lubricant having a moisture content of less than 25 ppm. The tubes were then attached to a gas manifold of known volume and evacuated to < 13 Pa. The tubes were then cooled using liquid nitrogen and individually charged with predetermined amounts of refrigerant using pressure change to accurately control the amount of refrigerant added. Each tube was then flame sealed and slowly warmed to room temperature. The total volume of lubricant/refrigerant in each tube was fixed at 2.0 mL regardless of the concentration of lubricant in refrigerant. The tubes were then secured in a computer controlled temperature chamber quipped with a video camera. The chamber temperature was then changed at a controlled rate of 0.1 °C per minute while the video camera recorded any changes in the phase behavior of the refrigerant/lubricant mixtures in the tubes. The temperature change was always made starting at room temperature and either going up or down in temperature until the first signs of incompatibility (cloudiness) was observed. Both upper and lower critical solution temperatures were taken as the first point when a haze was observed. Measurements were conducted in the temperature range of -60 to 70 °C.

2.2 Refrigerant/Lubricant Thermophysical Data Measurements

Solution properties as a function of Pressure, Viscosity, and Temperature (PVT) were determined using the test equipment described by Seeton (2009) to collect data to obtain constants for the set of solubility, density, and viscosity refrigerant/oil equations (Seeton and Hrnjak, 2006). The PVT test equipment is illustrated in Figure 1. The construction provides a circulation loop to maintain thermodynamic equilibrium during a slow temperature ramp. A pump circulates the fluid and promotes mixing; a mass flow meter measures rate flow, temperature, and density of the fluid; a piston viscometer measures temperature and viscosity; thermocouples measure bulk liquid phase and vapor phase temperature; and a pressure transducer measures system pressure. The loop is placed inside a thermal chamber that maintains constant temperature or a ramp temperature small enough to maintain a thermodynamic equilibrium when it sweeps a range of temperature at a constant bulk composition (Seeton, 2009). A desktop computer records the set of properties for each run for regression analysis.

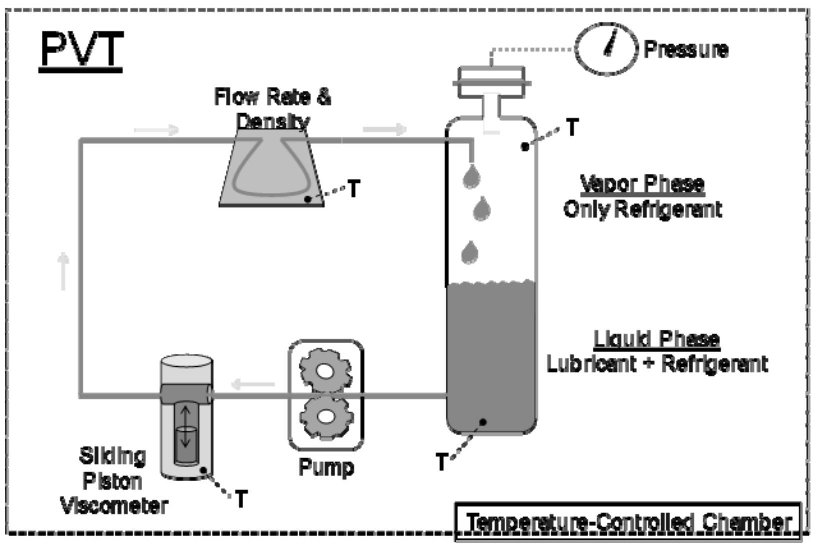


Figure 1: PVT Test Equipment

3. RESULTS AND DISCUSSION

3.1 Refrigerants of the Study

The compositions of the refrigerant blends of the study are shown in Table 1. The compositions of R-449A and R-449B are essentially the same and so for the purposes of this paper they will be considered together with the designation R-449A/B.

3.2 Polyol Ester Lubricants of the Study

All three polyol ester (POE) lubricants of the study were ISO 32 viscosity grade. The primary difference in the lubricants was their relative compatibility with the refrigerants. The miscibility of lubricants divided into three basic categories; fully miscible, partially miscible and non-miscible. Fully miscible lubricants are defined as those that remain as a single phase with the refrigerant of interest over the entire range of relative mixing ratios within the temperature range of -60 C to +70 C. Non-miscible lubricants are those that form a separate phase from the refrigerant of interest over the entire range of mixing ratios within the temperature range of -60 C to + 70C. Partially miscible lubricants are those that show a mixture of single phase and 2-phase behavior as a function of temperature and relative mixing ratios. The latter are the most prevalent type of lubricants used today with HFC refrigerants. The predominant commercial ISO 32 lubricant used today with R-404A is fully miscible.

Table 1: Refrigerant Blend Compositions of the Study

Refrigerant Component	R-404A	R-448A	R-449A	R-449B
R-125	44.0	26.0	24.7	24.3
R-134a	4.0	21.0	25.7	27.3
R-143a	52.0			
R-32		26.0	24.3	25.2
R-1234yf		20.0	25.3	23.2
R-1234ze		7.0		

Table 2: Physical Properties of the POE Lubricants of the Study

Lubricant	POE 1	POE 2	POE 3
KV @ 40 °C	31	31	30
KV @ 100 °C	5.3	5.6	5.6
Viscosity Index	129	135	145
Density (Kg/L)	0.998	0.970	0.967
Pour Point (°C)	-60	-45	-26
Flash Point (°C)	270	266	266
Refrigerant Miscibility			
R-404A	Fully Miscible	Partially Miscible	Not Miscible
R-448A	Fully Miscible	Partially Miscible	Not Miscible
R-449A/B	Fully Miscible	Partially Miscible	Not Miscible

3.3 Miscibility of the Lubricants in Refrigerants

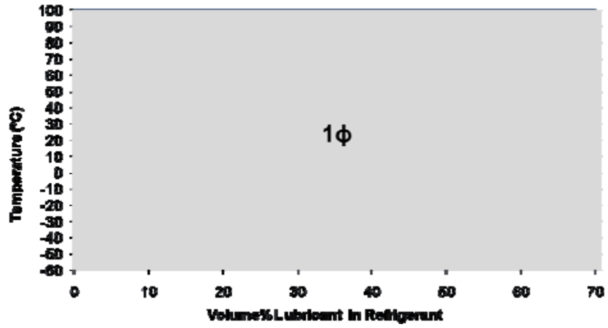
Lubricants generally fall into one of three categories with regards to miscibility with refrigerants as illustrated in Figure 2. It should be noted that although the “Not Miscible” category still contains a single phase region, this region is only at very high lubricant to refrigerant ratios where the lubricant dominates the cohesive properties of the mixture. Any lubricant/refrigerant combination that is completely immiscible at all temperatures below a lubricant/refrigerant ratio of 1:1 is, in all practicality, “Not Miscible”.

The majority of POE lubricant/HFC refrigerant mixtures used commercially today would fall into the “Partially Miscible” category. However, for refrigerants like R-404A used in low temperature applications, the desire is to have miscibility (single phase behavior of the mixture) that extends below -40 °C. Thus, most POE’s are fully miscible with R-404A.

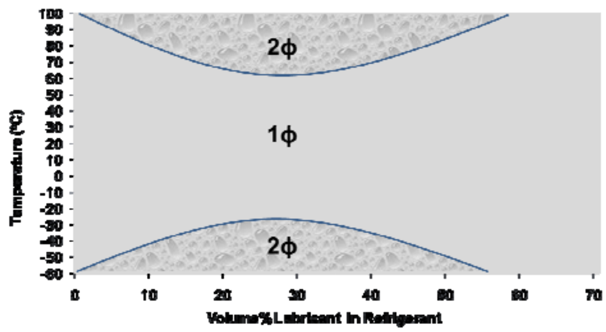
The miscibility of each lubricant, having varied polarity properties, was evaluated in each of the three lower GWP refrigerants and compared to that of R-404A. The results indicate that each of the low GWP refrigerant blends has relatively similar miscibility to R-404A (see Table 1).

3.4 Conditions for Reporting Solution Viscosities

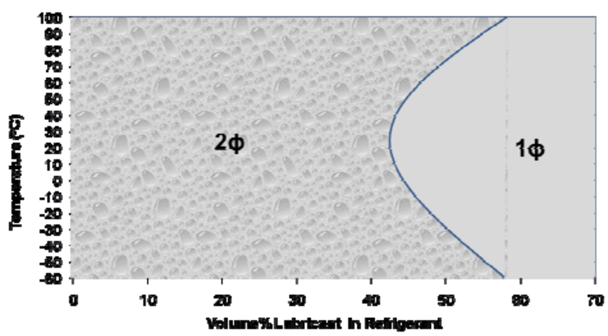
The ranges for reporting the solution viscosities of various combinations of lubricant and refrigerants are taken from actual measurements of suction and discharge temperatures taken from full system tests (Abbas, 2016). Although measurements were taken for a total of nine different conditions (Table 3), for the purposes of this paper, data will only be reported for one set of conditions (setting number 7). This one condition was taken as representative of a low temperature cooler in a modern grocery store. But it should be noted that the subsequent analysis presented in this paper for this one condition can equally be applied to the other sets of testing conditions.



Fully Miscible



Partially Miscible



Not Miscible

Figure 2: General Categories of Miscibility Between Lubricants and Refrigerants

Table 3: Ambient Temperature and Evaporator Settings for Calorimeter Measurements

Setting Number	Ambient Temperature (°C)	Evaporator Temperature (°C)
1	15.5	-9.4
2	29.4	-9.4
3	40.5	-9.4
4	15.5	-17.8
5	29.4	-17.8
6	40.5	-17.8
7	**15.5**	**-28.9**
8	29.4	-28.9
9	40.5	-28.9

The suction/discharge temperatures and pressures for each combination of refrigerant and lubricant are reported in Table 4. The combination of R-404A with POE1 is included as a reference as this refrigerant/lubricant combination is used commercially today. Experimentally temperatures and pressures were not available for R-448A/POE 1 combination, however, values were estimated by simply averaging the suction and discharge temperatures and pressures from R-449A/B experimental data. This was considered valid based on the near equivalence of the critical temperatures, pressures and densities of R-448A and R-449A/B.

Table 4: Suction/Discharge Temperatures and Pressures

Refrigerant	R-404A	R-449A/B	R-449A/B	R-449A/B	R-448A
Lubricant	POE 1	POE 1	POE 2	POE 3	POE 1
Suction Temp. (°C)	-9.5	-4.4	-11.4	-7.0	-7.6*
Discharge Temp (°C)	44.7	54.8	54.3	55.1	54.7*
Suction Pressure (KPa)	169	147	144	140	144*
Discharge Pressure (KPa)	1579	1576	1567	1560	1568*

*Estimated as described in text.

3.5 Variation in Solution Viscosity as a Function of Refrigerant Composition

The solution viscosity of a single ISO 32 POE (POE 1) was compared under both suction and discharge conditions for the low GWP alternatives R-448A and R-449A/B vs. R-404A as control. The viscosity under suction conditions is very representative of the viscosity of the liquid lubricant/refrigerant in the sump of a compressor. At suction, the solution viscosity of both low GWP alternatives R-448A and R-449A/B are essentially identical over the temperature range of -12 °C to 55 °C (Figure 3). The viscosities are always lower than that of R-404A, suggesting higher solubility of these refrigerants in POE 1 at low temperatures and pressures. But the absolute viscosity is always in the range of 30-150 cSt which would be anticipated to be acceptable for proper lubrication of bearings in the sump of a reciprocating compressors. The difference in the viscosities between R-404A and the alternatives also disappears as the temperature increases. This effect is due to the fact that refrigerant is driven from the lubricant as the temperature increases so the observed viscosity becomes a function of the lubricant alone at low pressure.

The solution viscosity as a function of temperature for the discharge conditions are shown in Figure 4. The isobaric discharge viscosity lines are representative of the viscosity of the liquid refrigerant/lubricant mixture as it leaves the discharge port. Note that the viscosities are much lower than the corresponding suction viscosities (Figure 3). The discharge liquid contains a high concentration of refrigerant. Because this liquid has no practical role in lubricating important moving parts of a typical reciprocating compressor, there is no concern that such viscosities are so low But there might be implications for scroll compressors where lubrication and sealing are required over the entire range of temperature/pressure from suction to discharge.

3.7 Variation in Solution Viscosity as a Function of Lubricant Type

POEs with varying degrees of miscibility with the low GWP refrigerants were compared in a single refrigerant (R-449B). The suction condition viscosity curves are shown in Figure 5. For all cases, the solution viscosities were virtually identical, despite significant differences in compatibility of the POEs with R-449B. This is somewhat surprising, but also highlights the fact that, regardless of the observed miscibility behavior, all of the lubricants have similar solubility with R-449B at very high lubricant:refrigerant ratios. The solution viscosity curves for three different lubricants of different compatibility with R-449B are shown in Figure 6. Here, where the concentration of refrigerant is high and the viscosity is low, there is a trend in observed viscosity as a function of the compatibility/solubility of the lubricant with the refrigerant. The non-miscible lubricant (POE 3) gives the highest viscosity curve while the fully miscible lubricant (POE 1) gives the lowest viscosity curve. Regardless, the differences are small.

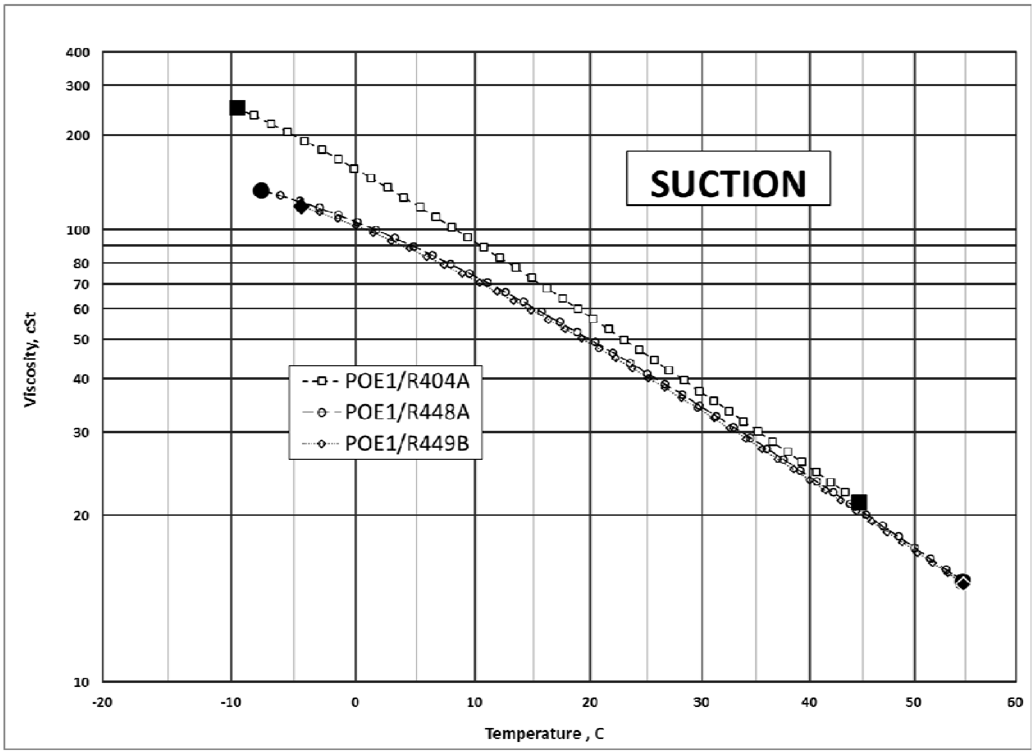


Figure 3: Suction Condition Solution Viscosity Curves for Three Refrigerants with a Single Lubricant

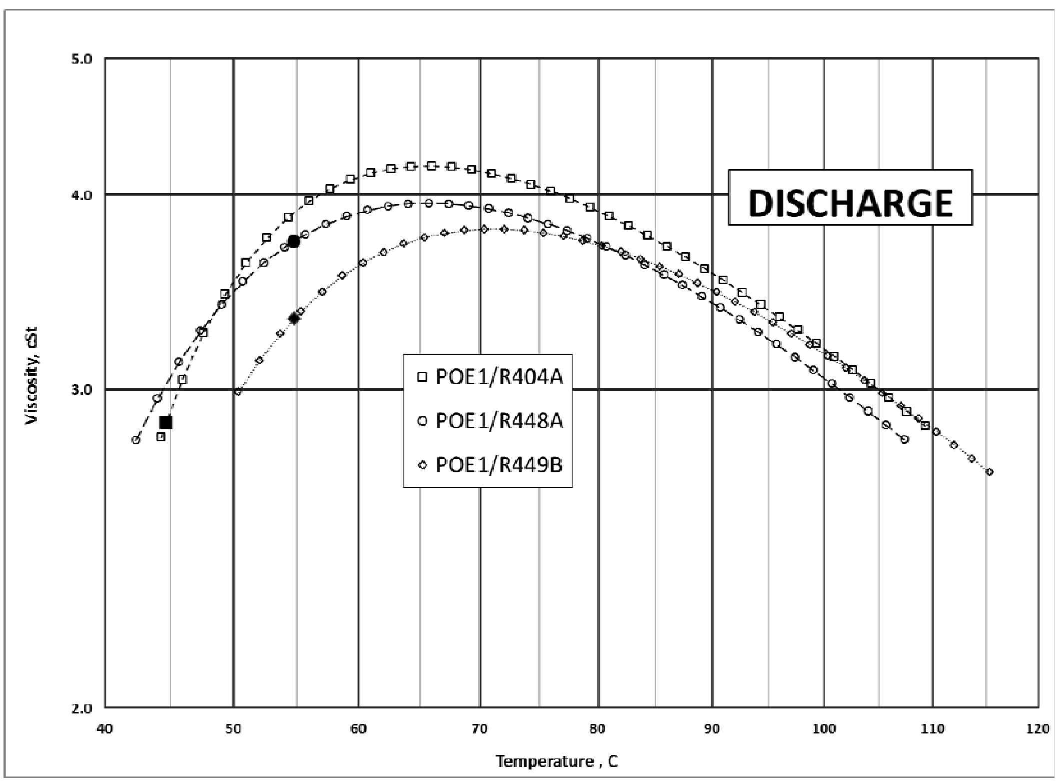


Figure 4: Discharge Condition Solution Viscosity Curves for Three Refrigerants with a Single Lubricant

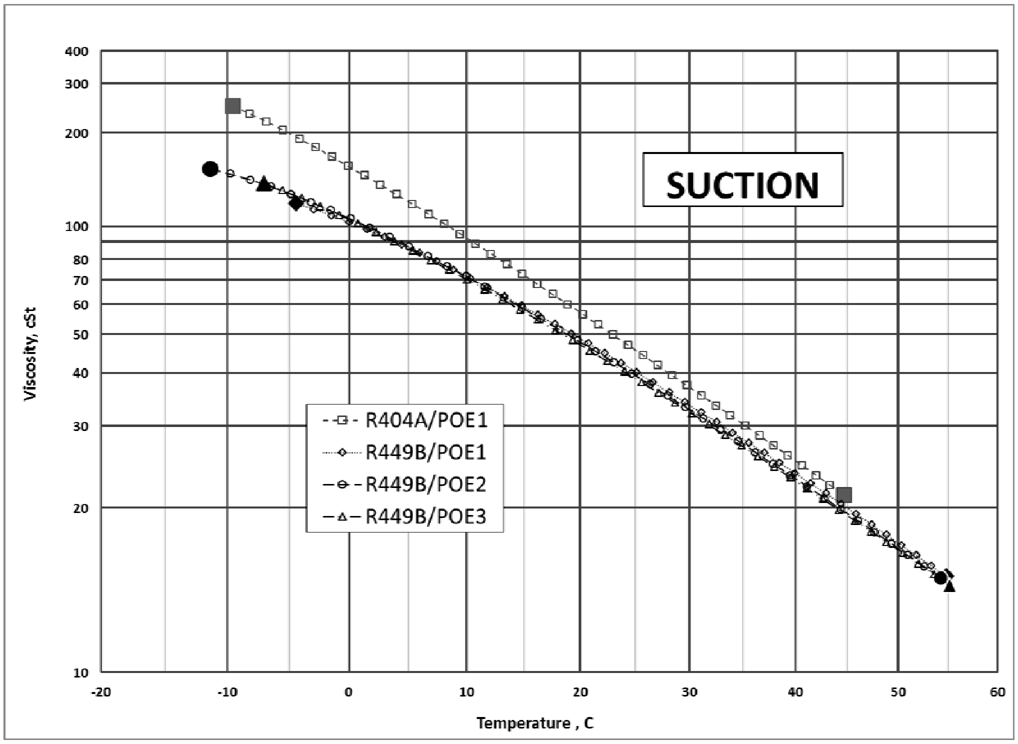


Figure 5: Suction Condition Solution Viscosity Curves for Three Lubricants with a Single Refrigerant (R-404A/POE 1 shown as reference)

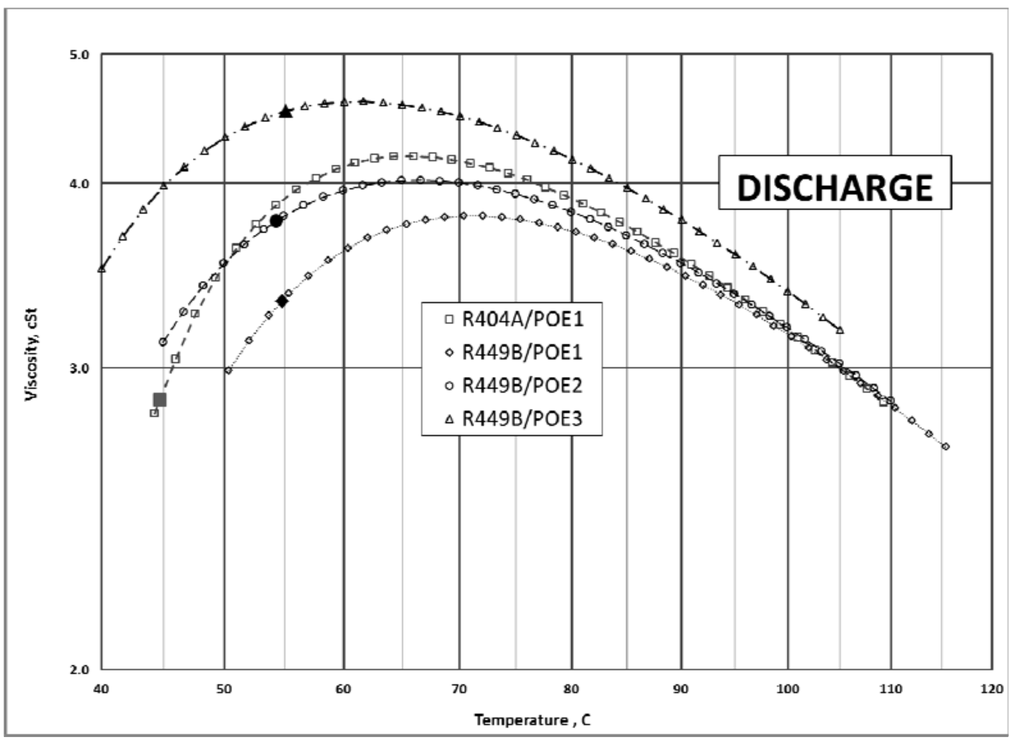


Figure 6: Discharge Condition Solution Viscosity Curves for Three Lubricants with a Single Refrigerant (R-404A/POE 1 shown as reference)

4. CONCLUSIONS

The solution properties of three ISO 32 POE lubricants of different miscibility/compatibility with several low GWP R-404A replacement refrigerant blends was studied. Comparison of suction and discharge isobaric viscosity curves for a single ISO 32 POE with all three refrigerants shows that all of the low GWP replacements have similar viscosity profiles to that of R-404A. This not surprising in that it is likely that a design criteria for all of the blends was near equivalent miscibility and solubility behavior with currently used commercial ISO 32 POE lubricants.
Comparison of the suction and discharge solution viscosity curves for three different lubricants with one low GWP refrigerant (R-449B) shows very little difference in solution properties despite the large variation in the solubility/miscibility properties of the ISO 32 POEs. The overall conclusion of this study is that the current commercial ISO 32 lubricants used today with R-404A can also be safely used with low GWP replacement refrigerants R-449A/B and R-448A. There is no reason to believe that there will be any lubricant related issues with system performance and/or equipment reliability.

5. NOMENCLATURE

AHRI	Air-Conditioner Heating and Refrigeration Institute	(–)
AREP	Alternate Refrigerant Evaluation Program	(–)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	(–)
ASTM	American Society for Testing and Materials	(–)
°C	Degrees Celsius	(–)
cSt	Centistokes (viscosity)	(millimeter/second^2)
GWP	Global Warming Potential	(–)
HCFC	Hydrochlorofluorocarbon	(–)
HFC	Hydrofluorocarbon	(–)
HFO	Hydrofluoro-olefin	(–)
KV	Kinematic Viscosity, Centistokes	(millimeter/second^2)
POE	Polyol Ester	(–)
ppm	parts per million	(milligram/liter)
kPa	kilopascals	(killogram/meter·second^2)
PVT	Pressure-Viscosity-Temperature	(kPa-cSt- degrees centigrade)

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